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INSTITUT NATIONAL DE RECHERCHE EN INFORMATIQUE ET EN AUTOMATIQUE

*Multi-mode relaying for power consumption
reduction*

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AMMAR — Clément REBOUL

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Multi-mode relaying for power consumption reduction

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Abstract: As multi-mode is becoming standard in current mobile terminals, the necessity to reduce power consumption increases. In this paper, we propose to utilize multi-mode to cut the energy needs, by relaying on the least power consuming communication mode. The most convenient way to implement multi-mode is undoubtedly provided by Software Defined Radio (SDR). The idea is to replace the ever-increasing embedded radio chips by a single, general purpose, processor.

We show that a multi-mode relay, composed of Software Defined Radios, has an impact on power reduction. We elaborate different scenarios to verify this proposition, considering that this multi-mode ability is based on an SDR. Firstly, we propose an 802.11g-to-UMTS relay scheme, where a mobile terminal relays other users' signal. We enounce different rules to minimize the global power consumption through multi-mode relaying. Then, we find different results for an 802.15.4-to-802.11g relay. After further inquiries, we explain how the most intuitive solution is not always the best one. Following a more realistic approach, we use network simulations to determine the important parameters having an impact on power consumption.

Key-words: multi-mode relay, software defined radio, power reduction

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Relai multi-mode dans un but de réduction de la consommation d'énergie

Résumé : Les terminaux mobiles actuels possédant tous plusieurs interfaces de communication en standard (ils sont dits multi-mode), il devient nécessaire de réduire leur consommation d'énergie. Dans ce papier, nous proposons de réduire les coûts énergétiques, grâce à la mise en place d'un relai sur le mode de communication le moins consommateur d'énergie. Pour ce faire, nous basons notre travail sur les spécifications de la Radio Logicielle, qui permet de remplacer l'accumulation de circuits de communication par un unique processeur générique. Ainsi, la Radio Logicielle permet une relative facilité d'implémentation du multi-modes.

Nous montrons qu'un relai multi-mode, composé de radios logicielles, permet de réduire la consommation d'énergie. Pour cela, nous élaborons différents scénarios dans le but de vérifier cette proposition, en considérant que le multi-mode est obtenu grâce à des programmes exécutés par la radio logicielle. Dans un premier temps, nous étudions un scénario de relai 802.11g-vers-UMTS, où un terminal mobile joue le rôle du relai pour les autres utilisateur. Nous énonçons différentes règles permettant la minimisation de la consommation globale du système, dans le cadre de ce relai multi-mode. Dans un second temps, l'application de ces règles à un relai 802.15.4-vers-802.11g mène à des résultats différents. Après examination, nous expliquons comment la solution la plus intuitive n'est pas toujours la meilleure. En utilisant une approche plus réaliste via des simulations réseaux, nous déterminons plusieurs paramètres importants ayant un impact sur la consommation d'énergie.

Mots-clés : relai multi-mode, radio logicielle, réduction d'énergie

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1 Introduction

Multi-mode is an established feature in all current mobile terminals. By enabling communication on different modes, such as IEEE 802.11g [14] or UMTS [1], this property brings us closer to an unlimited connectivity, an important need for all mobile users. A multi-mode terminal can switch its communication interface in order to connect to the best suitable mode, in term of application needs (QoS), users' choices (access cost), or energy reduction.

However, current devices rely on a number of dedicated chipsets to provide connectivity. With one chipset associated to one mode, the terminal cost is raising drastically along with its power consumption. A solution might lie in Software Defined Radio (SDR), where the multiple chipsets found in current devices are replaced by a single generic purpose processor running algorithms. Thus, a multi-mode SDR implements different modes as different algorithms. Since all modern standards share commonalities, those algorithms are reusable between different modes. This leads to a facilitated implementation of new modes, and a better power efficiency of parallel communications on two different modes.

Still, another problem remains. How can operators ensure an all time connectivity, without generating new costs? Relay usage is one possible answer. A relay is a device transmitting data from users in bad conditions to an access point. Such relays can be deployed by operators or be mobile. In the latter case, users' terminals act as potential relays.

In our work, we take advantage of a multi-mode relay in order to reduce the network global power consumption. In our mobile multi-mode relay, a Primary User (PU) communicates with Secondary Users (SUs) on one mode denoted R mode, and with an Access Point (AP) on another mode denoted D Mode. Contrary to classical works in the relaying field, we focus on the physical layer power consumption, including not only the transmission power but also numerical and analogical power consumptions. We do not consider the energy consumption induced by upper layer. An SDR brings many advantages when dealing with multi-mode: its adaptation possibilities benefit to the energy reduction. Since mobile terminals are power-limited, we propose a careful study of all elements (related to the physical layer) involved in their power consumption. Firstly, we evaluate the numerical complexity for different communication modes, which is closely tied to the power consumption in an SDR. We focus on the IEEE 802.11g (WiFi) [14], a WLAN standard, 3GPP UMTS [1], a voice and data long-range mobile communication mode, and the IEEE 802.15.4 low-power WPAN (Zigbee) [15].

We explore a list of the current related works in the SDR and relay domains, as well as their usages in power reduction, and expose our approach in section 2. We detail the previous stages concerning the complexity evaluation and the numerical power consumption in section 3. We also present the analogical power consumption and different channels models, in section 4. We then look at the energy consumption of different relay scenarios, where PU is relaying an 802.11g-connected SU to UMTS gateway. We estimate the power consumption of a mobile PU acting as a relay for a fixed or several Secondary Users (SUs) with the cost of direct UMTS connections. We also study the behaviour of a relay at fixed distance from a SU. We realize those scenarios through Matlab simulations and express relay rules to reduce the global power consumption, in section 6. In addition, we study an 802.15.4-to-802.11g relay, and determine that a more realistic approach is needed. We show that analytical conclusions are not always the right ones, by taking into account the consumption of network control packets and

passive overhearing in a network simulator, WSNNet [9], in section 7. Finally, we discuss about the need of a realistic study to predict the power consumption behaviour of a multi-mode relay in section 8.

2 Software defined radio and relays, toward a lower power consumption

2.1 State of the art

Different works already study the benefits of SDR and relay. We present an overview of these works, focusing particularly on energy savings. Limiting the terminal power consumption remains at the core of many domains related to mobility: from the terminals conception to the applications and services usages. Multi-mode can help to achieve energy reduction, a critical issue in mobility. At the physical layer level, In-Whhee et al. select the less consuming mode with an algorithm taking into account the required quality of service, the cost for the user and the terminal remaining battery life in [17]. This approach raises the terminal lifetime for a given amount of data. Authors rely on realistic radio energy values to evaluate the terminal consumption but do not consider the numerical cost. While users tend to utilize mobile services, their discovery is a consuming process. A terminal can also benefit from multi-mode in a context of ubiquitous services as presented in [8]. The paper expresses the necessity of power reduction in a pervasive service discovery scheme, by reconfiguring a multi-mode terminal to communicate on the most energy efficient interface. However, the choice is not only lead by the lowest power consumption, but needs to take into account the service type. Authors denote that a “low-power” standard (here Bluetooth) is actually not the less consuming mode, due to a higher consumption per packet. However, they do not consider relaying.

As presented before, an SDR provides the adaptability required to change mode dynamically. Different works enhance and facilitate the terminal reconfiguration. Berlemann implements a realistic protocol stack, sharing processing blocks between 802.11g and UMTS [5]. However, this work is more focused on the network access and transport layers, instead of the physical layer. This gap is filled by Montium, a low-power SDR architecture, sharing processing blocks between different parallel modes [25]. Montium can be at the core of mobile SDR terminals, but requires an adapted programming of the different communication blocks, which must be preinstalled, or downloaded over the air. However, multi-mode is not evaluated.

An SDR has reconfiguration capabilities, which brings the flexibility needed to guarantee an always available connection. This reconfiguration, where the terminal changes mode, is decided by a metric based on different criteria. Although classical metrics look at the channel conditions as in [10], where the mode with the highest SNR is chosen, long term energy savings are not guaranteed. More interesting metrics take into account other parameters. Ganesan proposes a local metric, computed at the terminal, to evaluate the interferences caused by cognitive users for a primary user, both communicating on a licensed frequency [11]. When the primary user is detected, cognitive users negotiate with each other to change communication mode. Reconfiguration is at the centre of the IEEE SCC41 Working Group [16], via P1900.4 [12]. Their proposal is to send a small file, the radio enabler, containing all the needed information for the mobile terminal to select the best suitable network (number of operations per

second, frequency, data rate, and so on). Each mode having to broadcast its own radio enabler, it does not reveal to be power efficient.

The energy consumption cannot be reduced at the terminal only. Relaying allows users to connect to closer access points in the case of fixed relays, or to share their connection in the case of mobile relays. Jiang et al. apply reconfiguration to self-organized fixed relay stations [19]. To prevent handover process near cell border, different fixed relays communicate with the cellular network to evaluate the need of relaying a mobile user. This proposal reduces the radio power consumption and interferences, but not in multi-mode.

A relay has many advantages. It enables a better efficiency on network coverage as Cavalcanti et al. present an heterogeneous multi-hop wireless network [7]. In this network, mobile users can use other users' terminals as a relay to contact the access point through multi-hop communication. An algorithm estimates the "connectivity opportunity" from user preferences, data rate needs and channel conditions. Capacity and error rate improve but no estimation on the power consumption is given. Relaying reduces the transmission power. Wang, Srinivasan and Chua increase a sensor network lifetime up to four times thanks to mobile relays [30]. Relays are simple sensors with a larger battery. Mobile relays provide a better network autonomy, reduction of capacity bottlenecks, cost savings and more importantly, a normal behaviour of the mobile sensor when not acting as a relay.

Seddik et al. minimize the outage probability by dynamically adjusting the transmissions power values in Amplify-and-Forward multi-relay networks [26]. Their adaptive strategies bring a larger energy reduction than classical power allocation approaches, and at any distance from the access point, thanks to relaying. Nourizadeh et al. expose the advantages and disadvantages of mobile relay: greater network capacity, lower consumption when relaying a single user and cost savings in network deployment for an equivalent user satisfaction [24]. In cooperative clusters, a terminal has personal gains by sharing its connection for the good of the network: using adapted strategies, overall energy is saved [2, 3]. Those strategies allow communications at different data rates inside the cluster, and at a fixed data rate with the access point. However, authors only use radio power consumption, and do not consider multi-mode in the gain provided to multi-users.

As in SDR, the decision for a terminal whether to act as a relay or be relayed depends on a metric. Madan et al. improve global energy consumption in a cooperative network by using relays with beamforming capacity [22]. Authors compute the cost for each node to acquire its Channel State Information locally and select multiple relays through an adapted strategy, which guarantees the minimal consumption for an optimum number of relays. Hwang and Ko show that a sub-optimal relay selection avoids a constant listening of the channel conditions and thus, increases network lifetime [13]. Relay selection is performed after fading measurements. The impact of multi-hop relay selection on a sensor network power consumption is presented in [21]: the best relay is the one with the highest battery charge. Demonstrated with realistic front-end values, this energy optimized relay selection increases the network lifetime.

2.2 Our approach

In our approach, we include the numerical complexity in the terminal power consumption. We also implement network simulations for a more realistic evaluation of the power consumption, by taking into account control packets and passive overhearing. Our goal is to minimize the network global power consumption by combining SDR

and multi-mode relays. Compared to SDR, classical radios using one chipset per mode are not power efficient in multi-mode. The flexibility provided by an SDR allows power reduction, through multi-mode reconfiguration and resource sharing.

We show how the minimization of a terminal power consumption by communicating on the most efficient mode helps to reduce the global power consumption. Since an SDR implements a mode via processing blocks, we study the algorithmic complexity of 802.11g, UMTS and 802.15.4 for a given terminal. In order to compare those different modes, we evaluate the complexity for a single data bit and deduce the terminal numerical power consumption. We justify this per-bit approach as an appropriate way to discriminate different standards. Following these results, we compute the radio consumption for every mode and select the most efficient one. Thus, we minimize the terminal power consumption.

We combine several of those SDR terminals to form a multi-mode relay scheme, and evaluate the global power consumption. The scope of this paper is the physical layer power consumption, and thus, we do not consider upper layers in our estimation. We focus on the physical layer, including the numerical and analogical power consumption, unlike classical relay works which only take into account the transmission power.

In our relay proposal, one Primary User (denoted PU), whose terminal can act as a relay for one or several Secondary User(s) (denoted SU(s)), is in communication with an Access Point (denoted AP). Using Matlab simulations, we compare the power consumption of PU relaying SU with the cost of direct connections, for different cases in 802.11g-to-UMTS and 802.15.4-to-802.11g relays. We define the “No-Relay Zone”: a zone where relaying has no positive impact on global power consumption. Then, we express relay rules to minimize the global power consumption at all time, thanks to multi-mode relay.

Nevertheless, those rules are not applicable in the case of an 802.15.4-to-802.11g relay, due to the cost induced by MAC layer control packets and passive overhearing. Thus, we propose a more realistic evaluation, by relying on a network simulator. We choose WSNNet, a realistic wireless network simulator developed at the CITI Laboratory [9]. WSNNet is an open-source simulator providing realistic PHY and MAC layers, with a modular interface allowing rapid development of add-ons, coded in C. To perform our simulations, we designed a multi-mode WSNNet plugin and extended the power evaluation module by integrating the numerical consumption for each mode.

3 Complexity study

In software radio, a physical layer is implemented through programs. A multi-mode SDR runs different algorithms corresponding to the selected modes at the same time. To achieve our goal, we propose to communicate on the mode minimizing the SDR power consumption, which is composed of two parts: the numerical power consumption, depending on the algorithmic complexity, and the radio power consumption. In this section, we evaluate precisely the numerical complexity for the different algorithms used in 802.11g, UMTS and 802.15.4. As we compare different modes, we present the results as a number of operations per bit. We justify the relevance of this per-bit analysis in the purpose of comparing different modes.

Table 1: Important properties considered for the algorithmic complexity evaluation

802.11g		
Data bitrate	6 Mbps	54 Mbps
Carrier frequency	2,400 Mhz	
Physical layer	OFDM	
Encoding	Convolutional (rate 1/2)	Convolutional (rate 3/4)
Modulation	BPSK	64-QAM
Number of carrier	64 subcarriers (48 data, 4 preambles, 12 null)	
Spreading factor	-	
Chips per second	-	
Frame size (bits)	1500 * 8	
Header size (bits)	30 * 8	
UMTS		802.15.4
Data bitrate	384 kbps	20 kbps
Carrier frequency	1,900 Mhz (uplink) & 2,100 Mhz (downlink)	
Physical layer	Spreading & scrambling	Spreading
Encoding	Convolutional (rate 1/2)	Differential
Modulation	QPSK	BPSK
Number of carrier	1	1
Spreading factor	4	15
Chips per second	3.84 M	300 k
Frame size (bits)	3840	133 * 8
Header size (bits)	90 (DCCH: control channel)	8 * 8

3.1 A per-bit complexity analysis

The numerical complexity of a standard mostly depends on the selected parameters (*i.e.* modulation, code rate, ...). Complex bit transformations such as coding, spreading or OFDM mapping lead to a high complexity. Each mode has different steps in transmission, where databits are transformed, coded, modulated, assembled into frames, and sent to a receiver at a given radio bitrate. Our desire is to compare different modes on a common basis. Hence, we take into account all operations realized by a mode for a single data bit, and compute the number of operations per (data) bit, or *bitop*.

3.2 Algorithmic complexity evaluation

In order to evaluate the numerical power consumption, we compute the algorithmic complexity per bit, or *bitop*, for every mode, by referring to Neel, Robert and Reed's work [23]. This bitop value allows us to compare different standards. We proceed to a careful study of each mode physical layer to get per-bit results. In fact, the different databit transformations must be accounted for at each step: encoding, mapping, FFT, and so on. The number of operation for each step is first evaluated per frame (a necessary step in certain operations), before being converted into bitop and rounded up to the upper integer.

We present the bitop (rounded to the upper integer) for the transmission and reception chains in selected modes of 802.11g, UMTS and 802.15.4 on Table 2. The first noticeable result comes from the receiving operations needed to recover numerical bits. This costly process is required to correct all anomalies the signal encounters over the

Table 2: Detailed algorithmic complexity for selected communication modes (in bitop)

TRANSMISSION						
802.11g	6 Mbps	54 Mbps	UMTS	384 kbps	802.15.4	20 kbps
Scrambling	18	18	CRC	6	Coding	4
Coding	74	66	Coding	83	Spreading	15
Puncturing	0	26	Puncturing	18	Mapping	75
Interleaving	11	7	First interleaving	0		
Mapping	10	3	Frame segmenta- tion	7		
IFFT	195	22	Rate matching	7		
			Multiplexing	253		
			Second nterleaving	80		
			OVSF Spreading	20		
			Scrambling	80		
			Mapping	60		
			DCCH	131		
TOTAL TX	308	142	TOTAL TX	745	TOTAL TX	94
RECEPTION						
802.11g	6 Mbps	54 Mbps	UMTS	384 kbps	802.15.4	20 kbps
FIR filtering	9	1	FIR filtering	1,548	FIR filtering	108
Interpolation & decimation	53	6	Interpolation & decimation	555	Interpolation & decimation	65
Frequency adjust- ment	18	18	Slot synchroniza- tion	301	Frequency adjust- ment	2
Phase correction	2	2	Frame synchro- nization	36	Phase correction	2
Correlation	14	14	Descrambling	322	Correlation	1
FFT	195	22	Rake	80	Demapping	75
Demapping	10	3	DeMapping	60	Despreading	15
Deinterleaving	11	11	Second deinterleav- ing	80	Differential decod- ing	4
Depuncturing	0	26	Demultiplexing	253		
Viterbi decoding	155	188	Rate matching	7		
Descrambling	18	18	Frame desegmenta- tion	7		
			First deinterleaving	0		
			Depuncturing	18		
			Viterbi Decoding	248		
			CRC	6		
TOTAL RX	485	309	TOTAL RX	3,521	TOTAL RX	272

air. It is lower in 802.11g, which uses OFDM with a high data bitrate, and thus compensates the complexity by a lower bitop. As we can see, the most important bitops in 802.11g come from the convolutional encoding and IFFT in emission, from the Viterbi decoding and FFT in reception. Due to the BPSK modulation process, 6 Mbps is more costly than 54 Mbps, where intuition would lead to the contrary. However, the bitop is almost equivalent for higher datarates (24 Mbps, 36 Mbps, 48 Mbps and 54 Mbps). We choose to represent 54 Mbps only. In UMTS at 384 kbps, the multiplexing process has a high bitop cost due to the high number of memory access, while descrambling and Viterbi decoding represent a major complexity in reception. In UMTS, the bitop is more consequent at low rates, where the spreading is more important to achieve the required 3.84 MChips. Hence, the Rake complexity increases with the spreading factor. In 802.15.4, the mapping cost is largely induced by the high spreading factor. We did not evaluate the cost of 802.15.4 for other bitrates.

4 Power consumption estimation

We now evaluate the power required to transmit or receive one single data bit in the chosen mode, P_{bit} , the *power cost per bit*. As presented before, the terminal power consumption is divided into two parts : P_{num} , the numerical power consumption, and P_{rf} , the radio power consumption. P_{num} depending on the algorithmic complexities and the processor architecture. P_{rf} being tied to the radio front-end architecture and the transmission power output (dependant of the channel conditions), we consider a multi-band radio front-end adapted to multi-mode. Hence:

$$P_{bit} = P_{num} + P_{rf} \quad (1)$$

4.1 Numerical power consumption

After we have determined the algorithmic complexities for each mode, we evaluate the numerical power consumption, P_{num} (in Joule per bit), following [28]:

$$P_{num} = N * C * V_{dd}^2 \quad (2)$$

with N being the number of cycles, C the processor's switching capacitance (in Farad) and V_{dd} the input voltage (in Volt). For a given processor, at fixed frequency, the number of cycles increases with the algorithmic complexity. This leads to a higher power consumption. To express P_{num} in Joule per bit, we need to consider one operation per cycle and set N to the bitop evaluated previously. We consider the ARM 968E-S processor [4], running generic algorithms at one operation per cycle. For the required input voltage of $V_{dd} = 1.2V$, we calculate $C = 97.3pF$.

4.2 Radio power consumption

We separate the radio power consumption into two parts: the radio-frequency front-end power consumption, and the transmission power. The front-end power consumption depends on its architecture and activity. We consider a multi-mode radio-frequency front-end, capable of receiving simultaneously 802.11g, UMTS and 802.15.4 signals [6]. We evaluate the radio power consumption, P_{rf} (in Joule per bit), using [27]:

$$P_{rf} = N_T[(T_{on} + T_{st})P_{tx} + T_{on}P_O] + N_R(R_{on} + R_{st})P_{rx} \quad (3)$$

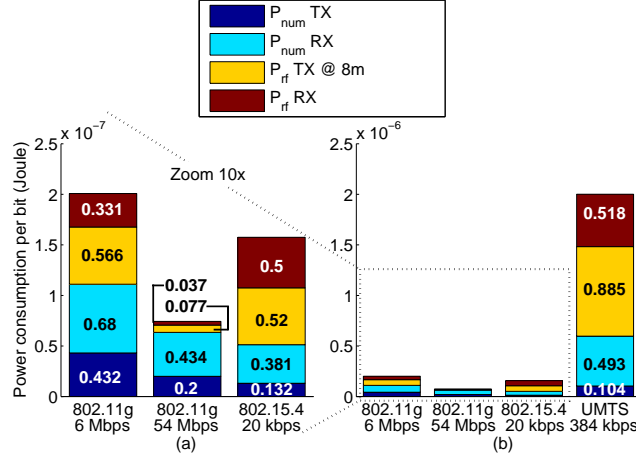


Figure 1: Terminal power cost per bit, P_{bit} , in Joule, for the transmitting and receiving component of P_{num} and P_{rf} . (a) zoomed on 802.11g and 802.15.4, (b) compared with UMTS.

with P_{tx} and P_{rx} (in Watt) being the power consumption of the front-end components, respectively when emitting and receiving and P_O the output signal power (in Watt). T_{on} and R_{on} represent the time to send or receive one data bit, T_{st} and R_{st} the wakeup time of the circuit in transmission and reception, N_T and N_R the amount of time the transmitter/receiver is switched on per period. We separate transmission from reception: for $N_T = 1, N_R = 0$ and reciprocally. We also set $T_{st} = R_{st} = 0$, because they are negligible in practice. The transmission power output, P_O , depends on the channel conditions and the distance with the receiver. We explain how to evaluate it in section 4.3. By setting T_{on} or R_{on} to the duration of a single databit, we express P_{rf} in Joule per bit.

We explore the energy needs to send and receive a single bit on Fig. 1. The numerical power consumption, P_{num} , remains constant at any distance. We observe the same behaviour for the radio reception. The radio power mostly depends on the transmission power, adjusted according to the receiver's channel conditions and distance. Indeed, the only varying parameter in the radio power transmission is P_O . As the distance increases, the radio consumption becomes predominant in the evaluation of P_{bit} . To obtain a good estimation, we evaluate the radio transmission power for a distance of 8 meters between two users.

We note the high cost of UMTS, due its high radio power consumption: the numerical power represents approximately a quarter of the radio power. In 802.11g, the numerical and radio power are almost identical to transmit and receive one data bit at 6 Mbps. At 54 Mbps, the radio energy is very low compared to the numerical part. This is due to the shortest time to send one single data bit. In 802.15.4, the radio and numerical parts have approximately the same cost.

We now compare the transmission and reception energy costs, by adding numerical and radio transmission. The high consumption of the transmission in low data rates is due to the time taken to send a single bit. In high data rates, the major energy needs come from the receiving side: the implemented algorithms, providing such speed, take a lot of processing power. Moreover, the increasing distance can also become a problem, by raising P_O too high. Focusing on the numerical side, we remark the

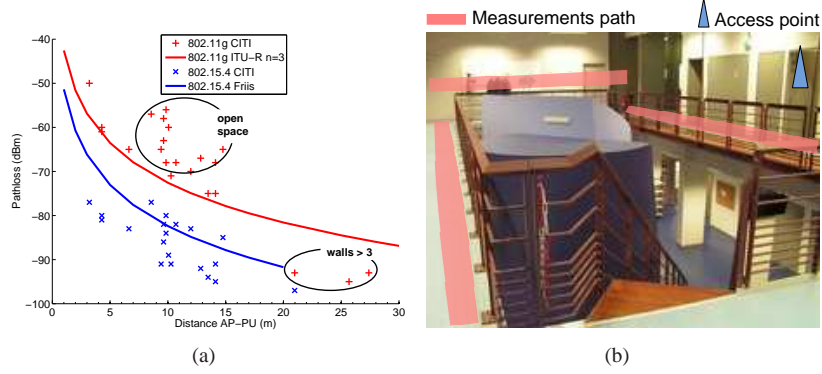


Figure 2: (a) Comparison of the channel conditions measurements and models. (b) A view of the CITI laboratory where the experiment took place.

predominance of the reception, as expected after Table 2. For any mode, the reception cost is up to five times the transmission.

4.3 Channel conditions

We select different channel conditions for every mode. We use an indoor-to-outdoor propagation model for UMTS, as users inside buildings communicate with an outside base station. We use indoor models for 802.11g and 802.15.4, mostly used inside buildings by nearby users.

The terminals control their transmission power by reducing P_O to the minimum value allowing the receiver to decode data properly. The required radio power to transmit a single bit is obtained by integrating P_O in (3).

Since, P_O depends on the channel conditions, we model the 802.11g, UMTS and 802.15.4 channels independently. We use the following Outdoor-to-Indoor empirical channel model in UMTS [20]:

$$L_{in,LOS,K} = 20\log_{10}(f) + 20\log_{10}(S + d_{in}) + 32.4 + L_{perp} + L_{par}(1 - \frac{D}{S})^2 \quad (4)$$

with $L_{in,LOS,K}$ the pathloss with line of sight (in dB), f the carrier frequency (in MHz), d_{in} the distance between the terminal and the outdoor, S and D the distances between the access point and the building (in m), respectively in line of sight and parallel to the ground, L_{perp} and L_{par} the wave penetration factors into the building (in dB), respectively for a perpendicular incidence and the line of sight angle. We take $L_{perp} = 10\text{dB}$, $L_{par} = 40\text{dB}$, $\frac{D}{S} = 0.4$, and the mobile terminal inside the building, $d_{in} = 10\text{m}$ from the walls.

We use an ITU-R office indoor channel model for 802.11g [18]:

$$L = 20\log_{10}(f) + 30\log_{10}(d) - 28 + L_f(n) \quad (5)$$

with L being the pathloss (in dB), f the carrier frequency (in MHz), d the distance between two terminals, 28 the freespace loss coefficient and $L_f(n)$ the floor penetration loss factor with n the number of floors penetrated. Here, $L_f(n) = 15 + 4(n - 1)$ for $n = 3$.

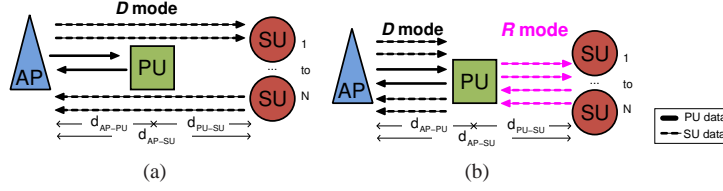


Figure 3: Scenario presentations. A Primary User (PU) acts as a relay for n Secondary Users (SUs). PU and SU communicate with the Access Point (AP) through (a) S_{direct} : Direct connections (b) S_{relay} : 802.15.4 Relay. D mode is the preferred communication mode with the Access Point, while R mode is the selected communication mode for the relay.

We rely on a classical Friis model for 802.15.4 indoor propagation:

$$L = n * [10\log_{10}(f) + 10\log_{10}(d) + 10\log_{10}(\frac{4\pi}{C})] \quad (6)$$

with L the indoor attenuation (in dB), f the carrier frequency (in Hz), d the distance between the two terminals (in m), and n the pathloss coefficient. After indoor measurements done at the CITI laboratory in 802.11g and 802.15.4, we take $n = 3.1$. As we can see on Fig. 2(a), those measurements permit a validation of the models with realistic values. The low variation of attenuation between 10 to 15 meters is due to the inside architecture of our laboratory: a large open space surrounded by catwalks visible on Fig. 2(b). Since the mathematical models follow the real pathloss values, we justify to use those models in the rest of the paper.

5 Multi-mode relay to achieve power reduction

5.1 Scenario presentation

We consider an Access Point (AP) and two SDR terminals, one is a Primary User (PU) capable of becoming relay, the other is a Secondary User (SU). The terminals communicate on a selected R mode with each other and on D mode with AP. D mode can be the same as R mode, or faster or slower. We apply a Rice fading to both signals, since the terminals are in line of sight.

We define the *global power consumption*, P_{global} , as the sum of all terminals' (but AP's) power cost per bit.

$$P_{global} = \sum_{i=0}^n P_{bit}(i) \quad (7)$$

with $P_{bit}(i)$ the terminal power consumption of user i . We choose to represent the PU power consumption, by $i = 0$, and SU_i the different secondary users, by $i > 0$. We compare the global power consumption, in Joule per bit, for the following cases, presented on Fig. 3:

1. S_{direct} : PU and SU communicate directly in D mode with AP (Fig. 3(a)).
2. S_{relay} : PU communicates in D mode with AP and acts as a relay. SU's signal is relayed in R mode on another D mode connection established by PU (Fig. 3(b)).

In the rest of the paper, we refer a PU relaying SU in R mode and connected to AP in D mode as a " R mode-to- D mode relay".

Table 3: Important parameters to consider for simulations

	802.11g		UMTS	802.15.4
Data bitrate	6 Mbps	54 Mbps	384 kbps	20 kbps
RF TX Value (mW)	338	338	338	1
RF RX Value (mW)	198.8 [6]	198.8 [6]	198.8 [6]	1 [29] +
Minimum P_O (dBm)	-20	-	-	-20
Maximum P_O (dBm)	10	-	-	0
RX Sensitivity (dBm)	-87	-71	-90	-92
Pathloss model	(5)	(5)	(4)	(6)
MAC Layer * Control packets size (bytes) *	CSMA/CA RTS: 36, CTS: 28, ACK: 26	CSMA/CA	FDD/TDMA -	CSMA (no RTS/CTS) -

⁺[29] proposes an integrated 802.15.4 transceiver with $P_{rx} = 3.28\text{mW}$ and $P_{tx} = 3.29\text{mW}$. As we separate the numerical and radio consumptions, we reduce our front-end consumption to 1mW.

*In network simulations only.

5.2 Protocols parameters in a multi-mode context

We present the different parameters needed to evaluate the terminal and the global energy consumption in Table 3. The RF TX and RX Value correspond to the radio front-end energetic consumption, P_{tx} and P_{rx} in (3). The receiver sensitivity is the minimum strength for a received signal to be decoded accurately. Pathloss models, introduced above, are needed to adapt the transmission power to the received signal strength. The calculation of P_O is the difference of that value with transmitted signal power minus the pathloss. The MAC layer and the size of control packets tell users the moment to send and receive data. We only need them during network simulations, and we show their importance in section 7.

6 802.11g-to-UMTS simulations

In this section, we present an analytical study of an 802.11g-to-UMTS relay power consumption. In this analytical study, we evaluate the complexity and power consumption of selected modes with no interferences, no control packets and no passive overhearing. We then implement S_{relay} and S_{direct} scenarios on Matlab, and compare their global power consumption.

6.1 Analytical study

An UMTS base station, abusively denoted AP in a matter of coherence, is emitting at controlled power to all its users. A Primary User (PU) is an SDR terminal which can act as a relay for Secondary User(s) (SU(s)), placed farther away from AP. For simplicity, AP, PU and SU are aligned, and all terminals follow a straight line when moving.

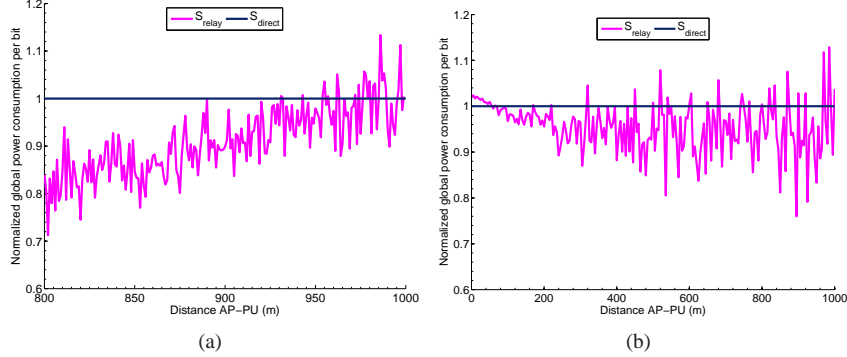


Figure 4: Global power consumption per bit, normalized by direct connections for different scenario. For a mobile Primary User (PU) and (a) a fixed Secondary User (SU) at $d_{AP-SU} = 1,000\text{m}$, (b) a Secondary User (SU) moving with PU at $d_{PU-SU} = 50\text{m}$.

In UMTS, a signaling process is continuously emitted by AP and received by all terminals for power control. In order to simulate these signals fluctuations, we apply an independent Ricean fading to all communications. Moreover, we resort to an uncapped P_O , so long range line of sight 802.11g communications can happen.

We evaluate the gains of relaying in the following scenarios (Fig. 4):

- PU is moving from AP toward a fixed SU, far from AP. S_{relay} brings 20% in power gains compared to S_{direct} , until PU moves closer to SU, where PU enters a “No-Relay Zone”: a zone where relaying has no major gain compared to direct connections. In the “No-Relay Zone”, S_{relay} consumption is 5 to 10% lower than S_{direct} . When PU is too close to SU, direct connections are privileged, as the gains are null, or negative, with 5% more energy required (Fig. 4(a)).
- PU and SU are separated by a fixed distance, d_{PU-SU} . They conserve this distance while moving together from AP toward the cell border. In this case, S_{relay} is interesting when PU and SU move farther from AP, with 5% gains on S_{relay} in average (Fig. 4(b)).
- PU is relaying multiple SUs, ranging from 1 to n . To express the worst case scenario, we place all n SUs at the position of the farthest SU. The global power consumption of S_{relay} of $n + 2$ SUs is better than S_{direct} consumption for n SUs, when PU is far from SUs. For the same number of SUs, the gains of relaying are near 35%. When PU is moving toward SUs, this gain lowers to reach 10 to 15% (Fig. 5).

6.2 Temporary conclusion

Based on the previous results, the following rules allow to minimize the global power consumption (Fig. 6).

When PU is close to AP (Fig. 6 ③), PU becomes a relay for SUs far from AP (Fig. 6 ①), with gains above 20%. By adding mobility, the terminal acting as a PU will relay for a certain period, before entering the “No-Relay Zone”. At that moment, PU stops relaying and becomes a new SU (Fig. 6 ①). Later, that terminal can become a new SU and be relayed by a new PU.

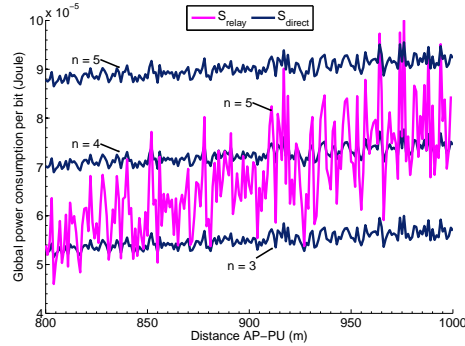


Figure 5: Global power consumption per bit, in Joule, with a Primary User (PU) acting as a mobile relay for n fixed Secondary User (SU). PU maintains $(n + 1)$ UMTS connections with the Access Point (n relayed SUs connections and its own). For n users, P_{bit} represents the average cost between uplink and downlink.

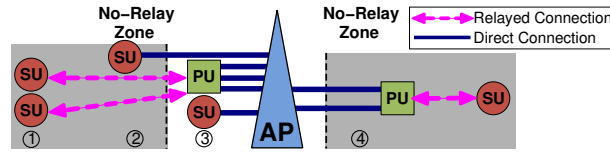


Figure 6: The different relay rules depend on the position of Primary Users (PU) and Secondary Users (SU).

When PU and SU are close from each other, and near AP, they communicate directly with AP (Fig. 6 ③). However, when they move together and reach the “No-Relay Zone”, PU and SU can decide to keep relaying (Fig. 6 ④), with 5% gains in average. If the distance between PU and SU raises, they contact AP directly.

All other approaches aiming at power reduction only consider the transmission power and forget the numerical power consumption. We have shown how important the numerical power consumption is in multi-mode, and have explained how to minimize the global power consumption using multi-mode relay.

In our work, any terminal following relay rules should limit energy depletion at long term. This way, by reducing a terminal power consumption, we minimize the global power consumption.

7 802.11g-to-802.15.4 simulations

In this section, we study the behaviour of relaying a slow mode on a fast connection. We select R mode as the IEEE 802.15.4 standard, also known as Zigbee. 802.15.4 is specifically designed for a low-power usage, and can be found in sensor networks or home automation systems. We relay a slow datarate on faster connections: we set D mode to 802.11g, with a bitrate of 6 Mbps. We also study the case of mono-mode relays, by setting R mode to 802.11g at 6 Mbps. PU is also moving on shorter distances. In 802.11g-to-UMTS, the environment was an indoor-to-outdoor environment, with a cell-radius of 1,000 meters. Here, we represent an indoor environment, where the maximum distance is around 20 meters. We implement more realistic simulations by

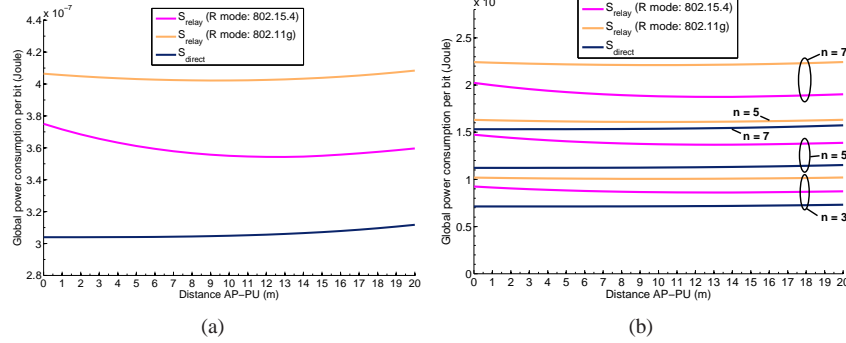


Figure 7: Global power consumption **analytical** comparison for S_{relay} in 802.15.4-to-802.11g and 802.11g-to-802.11g relay with S_{direct} . For n SUs, with (a) $n = 1$ and (b) $n = 3, 5$ and 7 SUs.

limiting the maximum transmission power, P_O . At first, we show the limitations of Matlab simulations and introduce the need of a more realistic approach by using a network simulator. Then, we present the different parameters having an influence on the energy consumption, in single and multi-users relays. We run the same scenarios described in section 5.1.

7.1 A crucial need to consider upper layers

We first focus on Matlab simulations presented on Fig. 7. We evaluate the global power consumption for a moving PU, and a fixed SU at $d_{AP-SU} = 20m$, on Fig. 7(a). The gain of S_{relay} is inexistent compared to S_{direct} for any R mode: an 802.15.4-to-802.11g relay requires 15% to 25% more energy, and an 802.11g-to-802.11g relay consumption is 25% to 30% higher, respectively close and far from SU. Comparing one relay to the other, 802.15.4-to-802.11g is only 5% to 10% better: direct connections are always more efficient. The greater cost comes from the radio power consumption: the time taken to send or receive a data bit is hundreds of time longer in Zigbee. Moreover, PU relaying on two 802.11g connections has no real advantage compared to direct connections at 20 meters. For a single moving PU, we conclude that a relay has no gain on the power consumption.

In case of multi-users relayed by a mobile PU, maintaining n connections presents critical losses as related on Fig. 7(b). The gains of relaying are getting worse as n increases: in average, relaying consumes between 20% and 30% more energy than direct connections. Those consumptions come from the highest cost of concurrent 802.11g connections, and the greater radio consumption of multiple 802.15.4 links at middle and long range.

7.2 Network simulations for a better precision

Since Matlab simulations only propose an analytical point of view, we rely on network simulations to study a more realistic behaviour. We choose WSNets, a realistic sensor network simulator, with cross-layer capabilities, developed at the CITI laboratory [9].

Networks simulations concentrate on the problems created by the upper layers, more specifically their cost on the physical layer consumption. For a clearer analysis,

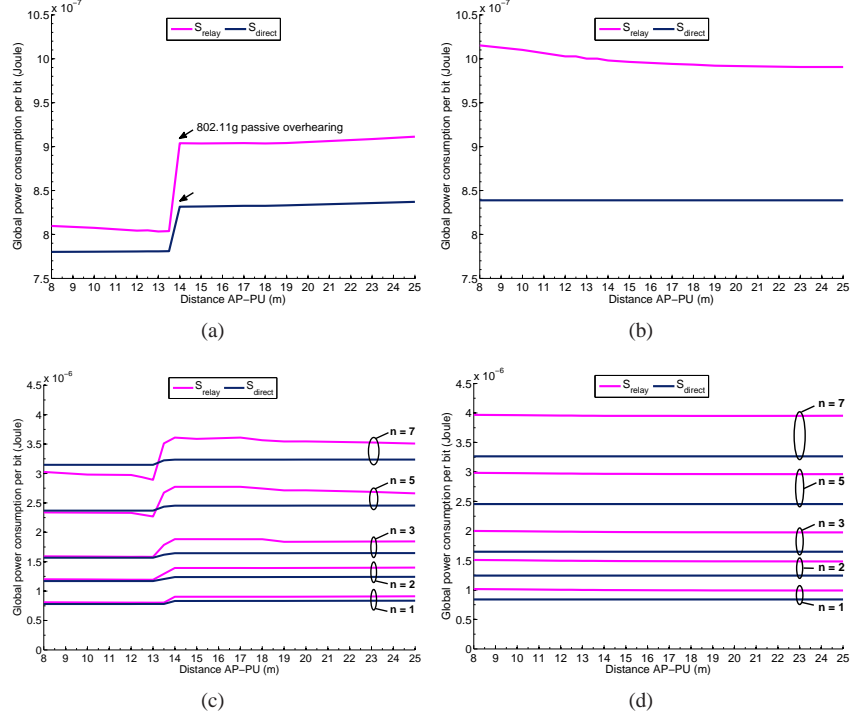


Figure 8: Global power consumption per bit, in Joule, **using a network simulator** for an 802.15.4-to-802.11g relay in S_{relay} and S_{direct} , with direct connection and with an 802.11g-to-802.11g relay. (a) and (c) in uplink for one SU and $n = 1, 2, 3, 5$ and 7 SUs. (b) and (d) in downlink for one SU and $n = 1, 2, 3, 5$ and 7 SUs.

we separate the uplink and downlink ways in every scenario. In downlink, AP sends data at the maximum transmission power and passive overhearing occurs: a terminal receives all signaling packets and its neighbours' data packets. In uplink, SU and PU desire to transmit data to AP: they must send control packets before accessing the medium. Passive overhearing also happens when users receive their neighbours' signals. We focus on an 802.15.4-to-802.11g relay, for S_{relay} and S_{direct} .

We evaluate the added cost of passive overhearing to the global power consumption on Fig. 8. In uplink, the ‘‘jump’’ happens when PU is exactly halfway between AP and SUs ($d_{AP-PU} = 14\text{m}$), as depicted on Fig. 8(a) for one SUs, and Fig. 8(c) for n SUs. When PU is close to AP, the 802.11g signal does not reach SUs due to the adaptation of the transmitted power, P_O . The consumption of S_{relay} is around 3% better S_{direct} , and reaches 5% for $n = 5$ SUs. However, once PU gets closer from SUs than AP, P_O rises so the signal can reach AP. Consequently, all SUs receive the data transmitted by PU, and S_{relay} consumes around 10% more energy than direct connections for any number of relayed SUs. Moreover, AP transmits at full power, thus all SUs receive control packets emitted by AP. In conclusion, the more SUs being relayed, the more the power difference between S_{relay} and S_{direct} raises, due to the greater amount of transmitted data.

In downlink, the difference coming from passive overhearing is not really perceptible, since PU does not send any data in 802.11g. Relaying is not interesting for one

or n SUs, with a power consumption 20% more important than S_{direct} , as presented on Fig.8(b)(d). Since we assume AP has an unlimited energy, we do not consider its power consumption. In S_{direct} , the global power consumption comes from the reception only. However, in S_{relay} , PU has to relay data from AP to SU. The transmission of R mode is taken into account. The cost introduced by those 802.15.4 connections remains too high to compensate 802.11g receptions at such distances.

7.3 Temporary conclusion

The first results show that an 802.15.4-to-802.11g relay has no real interest compared to direct connections, neither in uplink nor in downlink. We showed that such relay was not efficient through Matlab simulation, which lacked realism. After implementing the same simulations with more refined parameters on WSNNet, the relay power consumption remained above direct connections. Even though 802.15.4 has a higher radio consumption than 802.11g, it alone cannot explain the higher cost compared to multiple long range 802.11g connections. This has lead us to consider the influence of different parameters on power consumption.

We focus on two factors: passive overhearing, when SUs receive 802.11g data emitted by AP, and control packets, required before data transmission. When relaying on 802.15.4, we propose to neglect control packets by limiting their transmission power, and reduce 802.11g overhearing by disabling SUs' interface. In the next section, we quantify the gains of those two different approaches on relaying.

7.4 Network simulations with transmission constraints

As presented previously in section 7.2, network simulations allow us to observe the influence of control packets and passive overhearing on the network energy consumption. We evaluate two solutions to reduce the global power consumption: disabling SU's 802.11g radio interface, and limiting AP transmission power. The deactivation of the 802.11g interface at the SUs' drastically reduces the global power consumption as presented on Fig. 9, but might introduce problems: a multi-mode terminal works as a mono-mode one. In this case, denoted " S_{relay} with inactive 802.11g interface", SUs remove all costs linked to their 802.11g interface, and only suffer from 802.15.4 overhearing.

In uplink, deactivating the 802.11g interface at the SUs' gains around 35% of energy when PU is near AP, and over 40% when PU is approaching SU, as we can see on Fig.9(a). The more important energy consumption when PU is close to SU comes from the fact that PU sends 802.11g control packets at the maximum allowed power, to prevent hidden terminals. In downlink, high relaying gains are also noticeable on Fig 9(b), with an energy consumption reduced by 30% for one SU.

By default, 802.11g control packets are always transmitted at full power. Here, we limit the transmission power, so data and control packets only covers the distance between AP and PU. We apply this limit on both sides: PU control packets are also power-constrained. In this case, SUs' 802.11g interface is active and ready to receive. In uplink, when PU is close to AP, we notice a 35% power reduction on Fig. 9(a). For multi-users, relaying brings over 50% gains to the global power consumption, as presented on Fig. 9(c). Still, when PU is reaching half distance, the high cost of 802.11g passive overhearing makes this scheme reach 15% of S_{direct} global power consumption for one SU, and up to 30% for $n = 7$ SUs. For large values of n , when PU is too

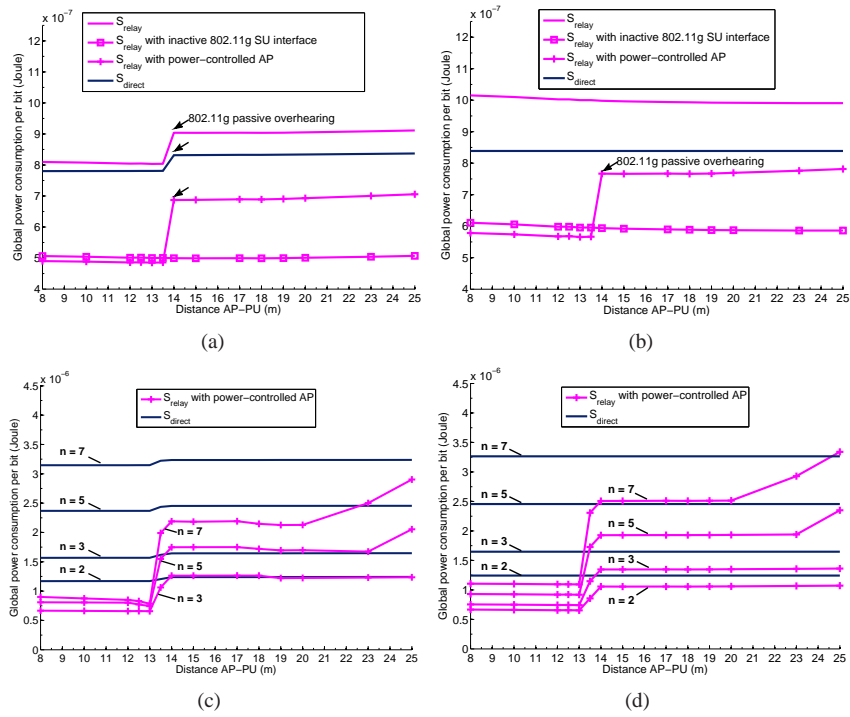


Figure 9: Global power consumption per bit, in Joule, using a network simulator for an 802.15.4-to-802.11g relay in S_{relay} and S_{direct} , with direct connection and an 802.11g-to-802.11g relay with power-controlled AP or 802.11g-disabled SUs' interface. (a) and (c) in uplink for one SU and $n = 2, 3, 5$ and 7 SUs. (b) and (d) in downlink for one SU and $n = 2, 3, 5$ and 7 SUs.

close from SUs, S_{relay} consumption increases due 802.11g passive overhearing, but still remains interesting (around 10% better for $n = 7$ SUs).

In downlink, relaying at limited power is the most interesting with a 30% gain when PU is near AP, as presented on Fig. 9(b): 802.11g control packets do not reach the different SUs. Relaying multi-users provides the same performances, as noticed on Fig. 9(d) with around 45% of energy saved for $n = 2$ SUs. At middle range, the relaying gain is lower, but still 7% more efficient than direct connections for one SU. For multi-users, the gains are more noticeable at middle-range, with 20% gains for $n = 5$ SUs. However, for PU close to $n = 7$ SUs, relaying is 2% worse than S_{direct} .

Power-constrained transmission allows to efficiently reduce the global power consumption, while not suffering of the disadvantages of 802.11g-deactivation at the SUs'. Compared to direct connections, this relay provides a lower cost and a good coverage for all users. However, the problem of hidden terminal remains. Hence, a new terminal must send a request to be detected, while PU should respond at full power during a very limited time. The new terminal might also be reported to AP by PU, if its maximum power is not sufficient. Moreover, current SUs might check the quality of their connection with AP: terminals can rely on a negotiation protocol established through the relay link, and ask AP to transmit at full power.

8 Discussion and conclusions

As we have seen, the 802.11g-to-UMTS relay brings noticeable costs improvements when PU is moving toward SU: between 10% and 15% in average. However, this scheme is subject to a "No-Relay Zone" where minimal gains occur. In 802.15.4-to-802.11g relay, the deactivation of 802.11g interface at the SUs provide over 50% in power reduction, but it causes several problems with the deactivation of multi-mode when new terminals arrive in the network. The power consumption of multi-mode mobile relays depends on different parameters, which we have detailed through realistic simulations. Each of those parameters must be carefully examined before taking any decision: their impact on relaying is important, and some intuitive solutions shall not be implemented promptly.

- Control packets: when using a realistic MAC layer, control packets specify when to access the medium. They also signal the good reception of data. Those packets must be accounted for in the energy needs of a mode. We have shown their importance by comparing Matlab and WSNets simulations. When relaying was supposed to be better, the reception of control packets by the secondary users lead to a more important global power consumption.
- Access Point transmission power: the limitation of the transmission power to only reach PU might lead to energy savings. However, when limited, a hidden terminal problem might occur. When a SU wants to communicate on D mode, it will not receive any control packets. This leads to probable collisions. We could prevent this by using a signaling protocol over the relay link, asking AP to raise its radio power on demand.
- Multi-mode overhearing: disabling the D mode interface at the relayed users' side should lead to a better efficiency. Nevertheless, the multi-mode capacity is lost, and mono-mode overhearing occurs on the same standard, raising the power consumption. Such measure requires periodic listening on the D mode interface,

to verify if maintaining the relay is still better than direct connections. This solution is preferred for relaying multiple users with a very low power consumption.

- Number of users: the more the number of secondary users relayed, the more costly passive overhearing is. This passive overhearing happens on D mode and on R mode. While considering D mode overhearing, disabling this interface at the SUs might be a solution. However, such technique is not always possible when dealing with multi-mode. A better solution requires an adapted MAC layer. A slotted MAC layer (such as TDMA) could answer those critics, though it introduces a delay increasing with the number of SUs. Evaluation of the optimal number of relayed users per PU is the response, but this is not the scope of this paper.

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